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Land cover and water yield: inference problems when comparing catchments with mixed land cover

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Abstract. Controlled experiments provide strong evidence that changing land cover (e.g. deforestation or afforestation) can affect mean catchment streamflow (Q). By contrast, a similarly strong influence has not been found in studies that interpret Q from multiple catchments with mixed land cover. One possible reason is that there are methodological issues with the way in which the Budyko framework was used in the latter type studies. We examined this using Q data observed in 278 Australian catchments and by making inferences from synthetic Q data simulated by a hydrological process model (the Australian Water Resources Assessment system Landscape model). The previous contrasting findings could be reproduced. In the synthetic experiment, the land cover influence was still present but not accurately detected with the Budyko- framework. Likely sources of interpretation bias demonstrated include: (i) noise in land cover, precipitation and Q data; (ii) additional catchment climate characteristics more important than land cover; and (iii) covariance between Q and catchment attributes. These methodological issues caution against the use of a Budyko framework to quantify a land cover influence in Q data from mixed land-cover catchments. Importantly, however, our findings do not rule out that there may also be physical processes that modify the influence of land cover in mixed land-cover catchments. Process model simulations suggested that lateral water redistribution between vegetation types and recirculation of intercepted rainfall may be important.

1 Introduction

1.1 Background

There is strong experimental evidence that changing land cover (e.g. deforestation or afforestation) can affect the local water balance. Such an influence has been detected at various scales, from site water balance and atmospheric water flux studies to small catchments undergoing change (see review by e.g. van Dijk and Keenan, 2007 and references therein). Controlled catchment experiments have demonstrated a change in mean catchment streamflow or (synonymously) water yield (Q) after land cover change (typically forest planting or logging; Bosch and Hewlett, 1982; Bruijnzeel, 1990, 2004; Andréassian, 2004; Brown et al., 2005; Farley et al., 2005). They appear to provide clear evidence that land cover characteristics affect Q , although this influence is moderated by a range of climate and catchment characteristics as well as vegetation attributes beyond broad land cover class alone (Andréassian, 2004; Bruijnzeel, 2004; van Dijk and Keenan, 2007). These conclusions could be corroborated by analysis of collated longer term Q estimates from multiple catchments, provided only catchments with (near complete) forest cover and herbaceous cover were selected (Holmes and Sinclair, 1986; Turner, 1991; Zhang et al., 1999, 2001). The collated data were still dominated by small experimental catchments, however, and such experiments are not without their challenges (discussed further on).

Subsequent studies have attempted to detect a similar land cover influence by statistically analysing Q from many catchments with mixed land cover. In such data sets, climate is the primary reason for variation in response and therefore

needs to be controlled for several studies do this by fitting an additive formulation of a Budyko model¹ (Budyko, 1974) that explicitly represents two (e.g. forest and herbaceous) or a small number of land cover types (Zhang et al., 2004; van Dijk et al., 2007; Oudin et al., 2008; Donohue et al., 2010; Peel et al., 2010). Such an approach has been described as a top-down analysis (*sensu* Klemesš, 1983; Sivapalan et al., 2003). In the following formula:

$$Q_j = \sum_i FC_{i,j} f(P_j, P_j, w_i), \quad (1)$$

where Q_j , P_j , and PE_j are the long-term (e.g. > 10 yr) average Q , precipitation and potential evaporation² (in mm per time unit) for catchment j , $FC_{i,j}$ is the fractional cover of land cover type i in catchment j , and w_i a dimensionless model parameter that characterises the hydrological behaviour of land cover class i and may be interpreted as a measure of the efficiency with which vegetation accesses and uses stored water. The influence of land cover is subsequently determined by finding the w_i values that minimise the root mean square error (RMSE) between observed and estimated Q , and interpreting the found parameter values. The cited studies performed such an analysis using collated data for 221 (Donohue et al., 2010) to 1508 (Oudin et al., 2008) catchments. They report either a much smaller land cover influence than found in controlled experiments (Zhang et al., 2004; van Dijk et al., 2007; Oudin et al., 2008; Donohue et al., 2010; Peel et al., 2010); no statistically significant influence (Zhang et al., 2004; van Dijk et al., 2007; Oudin et al., 2008; Peel et al., 2010); or even an influence opposite to that which might be anticipated – at least for some land cover classes (Oudin et al., 2008; Peel et al., 2010) or climate types (van Dijk et al., 2007; Peel et al., 2010).

It might seem surprising that land cover change would have a marked effect on the water balance of a catchment when it has homogeneous land cover, but not when it has mixed land cover. Some possible physical and methodological causes have been suggested. Physical explanations include:

1. *Catchment size.* The nature of controlled experiments puts a limit to the size of catchments that can be manipulated and the majority of experiments have been carried out on catchments smaller than 1 km² (see e.g. tabulated data in Andréassian, 2004; Brown et al., 2005). Conversely, data sets of real-world catchments with mixed land cover tend to have average catchment sizes in the order of hundreds to thousands km² (see respective studies listed earlier). A known issue with small catchments is the risk of ungauged subterranean transfers

¹ Defined here as any rational function that embodies the same conceptual model as the original (see various examples in e.g. Oudin et al., 2008).

² In evaporation we include all evaporation and transpiration fluxes.

(e.g. Bruijnzeel, 1990), which could lead to overestimation of the influence of land cover change on Q . Conversely, while land surface-atmosphere feedbacks perhaps can safely be ignored for small catchments, that may not be the case for large catchments, where land cover certainly influences overall evaporative energy and may even modulate precipitation (for discussion see Donohue et al., 2007; van Dijk and Keenan, 2007).

2. *Catchment hydrological processes.* As catchment experiments require small and well defined watersheds, they may be expected to have greater relief in comparison to larger catchments. Greater relief may mean shallower soils, less infiltration and therefore more storm flow, a more efficient surface drainage network, and lesser evaporation losses from streams, wetlands and groundwater-using vegetation (van Dijk et al., 2007).
3. *Land cover characteristics.* Experimental catchments may be expected to have a more idealised and homogeneous vegetation cover and fewer activities and structures designed to reduce storm runoff. In afforestation studies, the selection of suitable catchments may have created a bias towards low-complexity land cover, whereas land cover after clearing is unlikely to be representative of established agricultural landscapes. Large mixed land-cover catchments may include surface runoff intercepting features (e.g. hillside farm dams, tree belts) and unaccounted surface water or groundwater use (Calder, 2007; van Dijk et al., 2007). In addition, forest clearing in experimental studies may be associated with soil disturbance, which may enhance Q generation for reasons that are not directly attributable to land cover per se (Bruijnzeel, 2004). The consequence may be that the contrast in hydrological response between forest and herbaceous vegetation may be greater in experimental catchments than in non-experimental catchments. Finally, depending on the configuration of vegetation types within a catchment, forests may intercept and use lateral flows of water from herbaceous vegetation (further discussed in Sect. 4.2)

There are also some potential methodological issues:

4. *Other overriding climate and terrain factors.* Several studies have reported difficulty in detecting changes in the streamflow response of individual catchments as they undergo land use or land cover change, in large part because of the influence of climate variability (e.g. Beven et al., 2008; Peña-Arancibia et al., 2012). Confident detection and attribution of land cover influence requires that other factors are considered and controlled for Budyko theory controls for the two most important determinants of the long-term water balance, P and PE . One might question whether the Budyko framework is sufficiently powerful to evaluate effects in addition to P and PE alone, and if so, whether indeed land

cover is the next most important variable. Additional factors potentially equally or more important than land cover include the phase difference between seasonal P and PE patterns (Budyko, 1974; Milly, 1994) and other aspects of their temporal behaviour (e.g. rainfall intensity). Depending on their covariance with land cover, these attributes may attenuate or enhance any land cover influence on Q .

5. *Covariance between land cover and climate.* Covariance between land cover and climate is commonly present in collated catchment data sets due to the correlation between natural biomes and climate, and because of the role of landscape and climate in land use and land cover change decisions. For example, catchments with considerable remnant and plantation forests will usually be found more commonly in regions with greater relief, usually associated with greater P and lower PE than their lowland counterparts. Applying an additive response model to a data set with covariance between candidate predictors makes erroneous results more likely. Van Dijk et al. (2007) attempted to control for this effect and demonstrated that it influenced the results, but was probably not the only cause for the counterintuitive results they obtained.
6. *Measurement error.* Studies analysing data from small catchments have not been able to detect a significant change in stream flow when land cover is changed in less than 15–20 % of a catchment (Bosch and Hewlett, 1982; but see Trimble et al., 1987; Stednick, 1996). Arguably, this can be attributed to the influence of measurement noise on the analysis. Statistically, therefore it might be expected that it is harder to detect a land cover influence in large catchments with land cover mixtures than it is for catchments with homogeneous land cover. Using additive Budyko models requires estimates not only of Q , but also of catchment average P , PE and fractional cover (FC) of the land cover classes of interest. Errors will occur in each of these and may affect the analysis results, even more so if errors are not random. For example, Oudin et al. (2008) speculated that systematic precipitation measurement errors affected their analysis.

1.2 Objective

In this study, we aim to test the hypothesis that methodological issues with the use of a Budyko framework to interpret collated data from multiple mixed land-cover catchments may explain why a land cover influence has not been detected. To test this, we used Q observations from 278 non-experimental Australian catchments, the Zhang formulation of the Budyko model (Zhang et al., 2001), and a bottom-up dynamic hydrological process model with explicit representation of vegetation characteristics (AWRA-L). Synthetic

experiments were performed in which the Budyko model was used to analyse process model simulations for the 278 catchments. To paraphrase, we use the more complex model (AWRA-L) to create a virtual laboratory. We then perform a virtual experiment and use the Budyko model as an analytical tool to interpret the results. If our experiment can reproduce both a land cover influence for individual catchments as well as the lack of influence found in the type of multi-catchment studies described in the introduction, then this would support our hypothesis.

It is emphasised that we do not aim to prove that the methodological issues described are the single most important cause for the discrepancies arising from the discussed application of the Budyko model. Their presence certainly does not rule out the plausibility and presence of additional methodological or physical explanations. Several such explanations were mentioned and are further explored in the discussion (Sect. 4.2).

Strictly speaking, we are only able to test our hypothesis for the specified combination of catchment data, Budyko model formulation and process model. Moreover, we use models in our synthetic experiment as a plausible but not necessarily highly accurate representation of reality. This type of synthetic study is not unique but somewhat uncommon in the hydrological literature, and therefore we briefly discuss some caveats as to what are *not* our objectives.

Firstly, we do not aim to validate or falsify the dynamic process model (AWRA-L) we used in this experiment. We also do not aim to prove that the model structure and parameter values used here are the best possible description of reality, or better than any other model(s). Any model can only ever be a flawed and simplified abstraction of reality (e.g., Oreskes et al., 1994). Here we use the AWRA-L model because it is comparatively simple, because we understand it sufficiently well to interpret its behaviour and, most importantly, because it is able to reproduce two key features also observed in real data sets, as discussed in further detail below. Any other model able to meet this criterion should have been suitable for the experiment.

Secondly, we do not propose that we can use the more complex process model to prove a land cover influence; rather we show that it can reproduce such an influence in conditions where it has been observed as well as reproduce its absence in conditions where it has not. Proving the existence of a land cover influence is neither necessary (we refer to the empirical evidence discussed) nor possible (a model fundamentally cannot provide proof of a real-world phenomenon, at best only a plausible explanation). We will discuss this point in more detail further on.

Finally, we do not seek to falsify Budyko type models as a useful and predictive theory, or question the usefulness of top-down analysis as a paradigm. We focus here on only one very specific application: whether analysing collated data from mixed land-cover catchments by fitting a



Fig. 1. Location of the 278 Australian catchments for which stream-flow data were used in the analysis.

form of the Budyko model is able to accurately detect land cover influence.

2 Methods

2.1 Data

The Q data used here were identical to the data used by van Dijk and Warren (2010), which is a subset of 278 out of around 326 records used in previous studies (Guerschman et al., 2008, 2009; van Dijk, 2010a, c) and very similar in composition to Australian catchment data used in other studies (e.g. Zhang et al., 2004; Peel et al., 2010). Catchment boundaries were derived from a 9'' resolution digital elevation model (Fig. 1) and catchments with major water regulation infrastructure were excluded. The 278 catchments that were selected had data for at least five (not necessarily consecutive) years between 1990 and 2006 (median 16 yr). The woody vegetation cover fraction was mapped on the basis of Landsat Thematic Mapper imagery for 2004 and daily precipitation and Priestley-Taylor PE was interpolated at 0.05° resolution from station data (Jeffrey et al., 2001). Catchment areas varied from 23–1937 (median 278) km², tree cover from 0–90 % (median 25 %), P from 404–3138 (median 836) mm yr⁻¹, PE from 766–2096 (median 1265) mm yr⁻¹, and Q_{obs} from 4–1937 (median 114) mm yr⁻¹.

2.2 Budyko model

Oudin et al. (2008) tested five different Budyko model formulations and found little difference in their explanatory power, and all formulations have a very similar functional form. We chose the model of Zhang et al. (2001) because it was used successfully in previous studies to detect land cover

influence in a global Q data set of (mostly small) catchments with homogeneous land cover. For a single land cover class, the model can be written as

$$Q = \frac{P}{1 + \frac{P}{PE} + w \left(\frac{PE}{P} \right)^2}. \quad (2)$$

For a catchment with a two land cover classes, forest and herbaceous vegetation, Eq. (2) can be rewritten as (cf. Eq. 1)

$$Q = \text{FC (forest)} \frac{P}{1 + \frac{P}{PE} + w(\text{forest}) \left(\frac{PE}{P} \right)^2} + \text{FC (herbaceous)} \frac{P}{1 + \frac{P}{PE} + w(\text{herbaceous}) \left(\frac{PE}{P} \right)^2}. \quad (3)$$

2.3 Dynamic model

The dynamical model used is the Australian Water Resources Assessment system Landscape hydrology (AWRA-L) model (version 0.5; van Dijk, 2010b; van Dijk and Renzullo, 2011; van Dijk et al., 2012). AWRA-L can be considered a hybrid between a simplified grid-based land surface model and a non-spatial catchment model applied to individual grid cells. Where possible process equations were selected from literature and selected through comparison against observations. Prior estimates of all parameters were derived from literature and analyses carried out as part of model development. Full technical details on the model can be found in van Dijk (2010b) but some salient aspects are summarised here. The configuration used here considers two hydrological response units (HRUs): deep-rooted tall vegetation (forest) and shallow-rooted short vegetation (herbaceous). The water balance of a top soil, shallow soil and deep soil compartment are simulated for each HRU individually and have 30, 200 and 1000 mm plant available water storage, respectively. Groundwater and surface water dynamics are simulated at catchment scale. Minimum meteorological inputs are gridded daily total precipitation and incoming short-wave radiation, and daytime temperature. Maximum evaporation and transpiration given atmosphere and vegetation conditions are estimated using the Penman-Monteith model (Monteith, 1965). Actual transpiration is calculated as the lesser of maximum transpiration and maximum root water uptake given soil water availability. Rainfall interception is estimated separately using a variable canopy density version of the event-based Gash model (Gash, 1979; van Dijk et al., 2001a, b) to account for observed high rainfall evaporation rates (for discussion see e.g. van Dijk and Keenan, 2007). The influence of vegetation on the water balance occurs in a number of ways: compared to short vegetation, forest vegetation is parameterised to have lower albedo, greater aerodynamic conductance, greater wet canopy evaporation rates, lower maximum stomatal conductance, thicker leaves, access to deep soil and ground water, and adjust less rapidly to changes in water availability.

Van Dijk and Warren (2010) evaluated AWRA-L with the configuration and parameterisation used here against a range of in situ and satellite observations of water balance components and vegetation dynamics. This included evaluation against Q_{obs} from the catchments used in this analysis, as well as flux tower latent heat flux observations at four sites across Australia, including both forest and herbaceous sites (van Dijk and Warren, 2010). Latent heat flux patterns for dry canopy conditions were reproduced well. Comparison of total latent heat flux was difficult due to the large uncertainty in rainfall interception evaporation estimated from the flux tower measurements. Streamflow records were reproduced well, that is, with an accuracy that was commensurate to that achieved by other rainfall-runoff models with a similar calibration approach.

2.4 Experiments

2.4.1 Can previous contrasting findings be reproduced and reconciled with the process model?

We did two tests to see whether we could reproduce the contrasting findings of published analyses of Q from homogeneous experimental and from multiple non-experimental mixed land-cover catchments, respectively. First, we fitted the two parameter Zhang model (Eq. 3) by minimising the standard error of estimate (SEE) against Q_{obs} from the 278 catchments (using Solver in Microsoft ExcelTM). We interpreted the derived $w(\text{forest})$ and $w(\text{herbaceous})$ parameter values and implied land cover to assess whether we obtained the same contrasting findings as previous studies.

Next, we investigated whether the AWRA-L could reconcile these contrasting findings, which means meeting two conditions. First, the model needed to reproduce the observed Q from the 278 catchments as well as, or better than, the calibrated two-parameter Zhang model, as judged by several measures of agreement (Table 1). Second, the model needed to be in agreement with the results of experimental catchment studies of land cover change impacts on Q . One test of this would be to reproduce Q changes observed in an actual paired catchment experiment, but unfortunately we did not have access to daily streamflow and meteorological data for a number of such experiments, and one example would have a very limited statistical significance. Instead, we used AWRA-L to simulate Q from the 278 catchments under conditions of full forest and full herbaceous cover, respectively. We compared the resulting water balance estimates with the empirical relationships for the respective land cover type reported by Zhang et al. (2001), who propose two alternative models to estimate Q . The first method (Zhang-A) is to use Eq. (3) with values of $w(\text{forest}) = 2.0$ and $w(\text{herbaceous}) = 0.5$, with PE estimated using the Priestley–Taylor formula and a standard land cover with assumed albedo and aerodynamic conductance. The second method (Zhang-B) is to use the same approach, but substitute PE by

values of 1410 and 1100 mm yr⁻¹ for forest and herbaceous cover, respectively. The latter reduces the physical realism of the model, but provides a convenient alternative to where PE estimates are not readily available, and has been shown to agree well with other empirical relationships (Holmes and Sinclair, 1986; Turner, 1991) and data from catchments with homogeneous land cover (Zhang et al., 2001; Brown et al., 2005). These so-called Zhang curves have been widely used to estimate the impact of conversion between forest and non-forest cover on Q in scenario studies and policy reports (e.g. Austin et al., 2010; Brown et al., 2007; Dawes et al., 2004; Sun et al., 2006; van Dijk et al., 2006), and as such were considered a relevant point of reference. The vast majority of such reports assume that land cover impact is linearly proportional to the area of land cover change.

The prominent use of the Zhang curves in policy development puts further onus on understanding the apparent discrepancies between the results from the two experimental designs discussed. We emphasise that our objective does not require that the process model explains more variation than the Zhang models in one or both cases; equal or similar performance would be sufficient. The critical difference is that fitting the Zhang models typically leads to two substantially different parameter sets, essentially producing two mutually contradictory models in the respective applications. By contrast, the process model uses one parameter set only for both cases and therefore by definition produces internally consistent results. The process model parameters were estimated a priori rather than optimised, which is not essential but arguably preferable.

In summary, if the tests described above would be successful, we would be able to conclude that previous contrastive findings can be reproduced, and appear to be at least partly due to methodological problems. To put it differently: if the same process model with identical parameters can reproduce both (1) the land cover influence expected for individual catchments, and (2) the observed Q from mixed catchments, then the fact that two different parameter sets are required in the case of the Zhang model suggests a methodological problem with that particular inference approach.

The subsequent analyses were designed to try and analyse three potential methodological problems, viz. measurement errors, an overriding influence of other environmental factors, and covariance between land cover and climate.

2.4.2 Are measurement errors responsible?

One feasible explanation for the reduced or absent land cover impact inferred from catchments with mixed land cover is the possible impact of data error: P , PE, Q and forest cover fraction (FC) are all prone to measurement and estimation error. This could affect values for the two Zhang model parameters that were optimised. To test for this, we performed a synthetic experiment in which noise was added to the Q estimates produced by the process model (Q_{sim}), for the case

with actual, mixed land cover (we did not use the actually observed Q as this already contains measurement noise, with unknown characteristics). First, a simulated measurement error with an absolute average of 10% was added to all 278 original values of FC and mean P , PE and Q_{sim} . The errors were drawn independently for each variable and each catchment. For FC an error was added that was drawn from a normal (Gaussian) distribution with mean of zero and standard deviation of 0.1; the result was limited within the range 0 to 1. The values of P , PE and Q_{sim} were multiplied with a factor drawn from a normal distribution with mean of one and standard deviation of 0.1. Next, the two Zhang model parameters were optimised to the resulting noisy FC, P , PE and Q_{sim} values for all 278 catchments combined. This experiment was repeated 3000 times, each time with a sample of 278 catchments. The resulting 3000 pairs of w values were compared to those fitted to the original FC, P , PE and Q_{sim} values (i.e. without noise added), to assess whether the simulated measurement noise led to parameter values suggestive of a smaller than predicted land cover influence.

2.4.3 Are additional environmental factors responsible?

The premise of the Budyko framework is that mean P and PE are the main determinants of Q . Beyond this, however, other climate factors or terrain factors may be more important than land cover category. To investigate this possibility, we used the Zhang model to analyse the AWRA-L simulations for the forest and herbaceous scenarios. For each catchment, we calculated the model parameter (w) value corresponding to the Q simulated for each land cover scenario (i.e. full forest or full herbaceous cover) using the following inverted model form (cf. Eq. 2):

$$\frac{\frac{P}{Q_{\text{sim}}(\text{scenario})} - \frac{P}{\text{PE}} - 1}{\left(\frac{\text{PE}}{P}\right)^2}. \quad (4)$$

For each land cover category, we attempted to find catchment attributes that could explain the variance in inferred w values. We used the same step-wise regression approach used in earlier analyses of the same Q data (van Dijk, 2010a, c). In summary, candidate predictors were selected from a range of catchment attributes based on the parametric and non-parametric (ranked) correlation coefficients (r and r^* , respectively). Linear, logarithmic, exponential and power regression equations were calculated for all potential predictors, and the most powerful one was selected. The residual variance was calculated and the same procedure was repeated. The catchment attribute data available included measures of catchment morphology (catchment size, mean slope, flatness); soil characteristics (saturated hydraulic conductivity, dominant texture class value, plant available water content, clay content, solum thickness); climate indices (mean P , mean PE, humidity index P/PE , remotely sensed actual evapotranspiration, average monthly excess precipita-

tion); and land cover characteristics (fraction woody vegetation, fractions non-agricultural land, grazing land, horticulture, and broad acre cropping, remotely sensed vegetation greenness). Full details on data sources and catchment climate, terrain and land cover attributes can be found in van Dijk (2010a, c).

2.5 Is covariance between land cover and climate responsible?

Our catchment data set shows modest covariance between forest cover (FC) and P/PE ($r = 0.44$). Earlier analyses showed that this type of covariance can affect the ability to accurately determine land cover influence (see van Dijk et al., 2007, for a detailed example). We performed a further synthetic experiment using the AWRA-L model to test the magnitude of this problem:

1. Each of the 278 catchments was assigned a new virtual land cover by randomly drawing a new value for FC from a normal distribution with the same mean and standard deviation as the observed FC values (0.284 and ± 0.224 , respectively). Values were truncated to remain within the range 0 and 1.
2. For each catchment, the AWRA-L model was run with the new FC values and the original meteorological inputs.
3. The two Zhang model parameters were fitted to the resulting 278 Q_{sim} values.

The experiment was repeated 3000 times (each time with all 278 catchments), and the results were analysed to determine whether there was a relationship between any (randomly introduced) covariance between the FC and P/PE values on the one hand, and the inferred land cover influence on the other.

3 Results

3.1 Previous contrasting findings can be reproduced and reconciled by the process model

Indicators of the agreement between Q observed in the 278 catchments and values estimated by the optimised two-parameter Zhang model (Eq. 3) and the AWRA-L model are listed in Table 1. For comparison, the performance of the originally proposed Zhang-A and Zhang-B models and an optimised Zhang model (Eq. 2) are also shown. This comparison is important, as these two models incorporate the response of Q to land cover change as inferred from experimental catchment studies and widely used in scenario analysis.

Calibrating the Zhang model parameters led to an improvement in model performance and reduction in bias, when

Table 1. Performance indicators of the original Zhang et al. (2001) models (Zhang-A and Zhang-B; see text for explanation), the Zhang model with one and two calibrated parameters, respectively, and the AWRA-L with prior parameter estimates. All metrics relate to the agreement between modelled and observed mean annual streamflow (Q , mm per year) for all catchments ($N = 278$). SEE = standard error of estimate, MAE = mean absolute error, and Bias = mean bias (all in mm yr^{-1}); Rel. Bias = mean of absolute values of percentage bias and FOM = fraction of values overestimated by model (in %).

	SEE	MAE	Bias	Rel. Bias	FOM
Zhang-A	119	97	79	44 %	91 %
Zhang-B	136	114	86	47 %	86 %
Zhang – 2 parameter	84	54	4	2 %	62 %
Zhang – 1 parameter	84	54	4	2 %	62 %
AWRA-L	78	50	1	1 %	54 %

compared to the original models. However, reducing the Zhang model to a one-parameter model (that is, making the model insensitive to land cover), did not degrade model performance (optimised values were $w(\text{forest}) = 1.91$ and $w(\text{herbaceous}) = 1.98$ versus $w = 1.95$, respectively). These results support previously published result that fitting a Budyko model to observations from non-experimental catchments does not show the predicted land cover influence, in contrast with results based on experimental catchments. In other words, we were able to reproduce previous contrasting findings and reconcile them.

Table 1 also shows that, despite the lack of parameter optimisation, AWRA-L performs slightly better than the calibrated Zhang models. The AWRA-L predictions of Q for the same 278 catchments, but this time for a hypothetical scenario of full forest and herbaceous cover, are compared to the original Zhang-A and Zhang-B model in Fig. 2. AWRA-L is able to reproduce the approximate differences between forest and herbaceous catchments predicted by the original Zhang models, although the forest scenario predictions agree better with the Zhang-B model than with the Zhang-A model (Fig. 2). It follows that the process model (1) can predict Q from the 278 catchments with mixed land cover as well as (in fact, slightly better than) a fitted Zhang model, and (2) suggests a land cover influence of similar magnitude as that predicted by the original Zhang curves. Therefore, the process model can reconcile the contrasting conclusions drawn from experimental and mixed catchment Q data that the Zhang model cannot reconcile.

Further supporting this conclusion, the same results could also be reproduced when process model Q estimates were interpreted using the Zhang model. If a one-parameter Zhang model was fitted to the modelled Q_{sim} with hypothetical full forest or herbaceous cover, w values 3.6 and 1.0 were found, respectively – producing curves quite similar to the original Zhang-A and Zhang-B models. However, when the two-parameter Zhang model was fitted to the Q_{sim} obtained

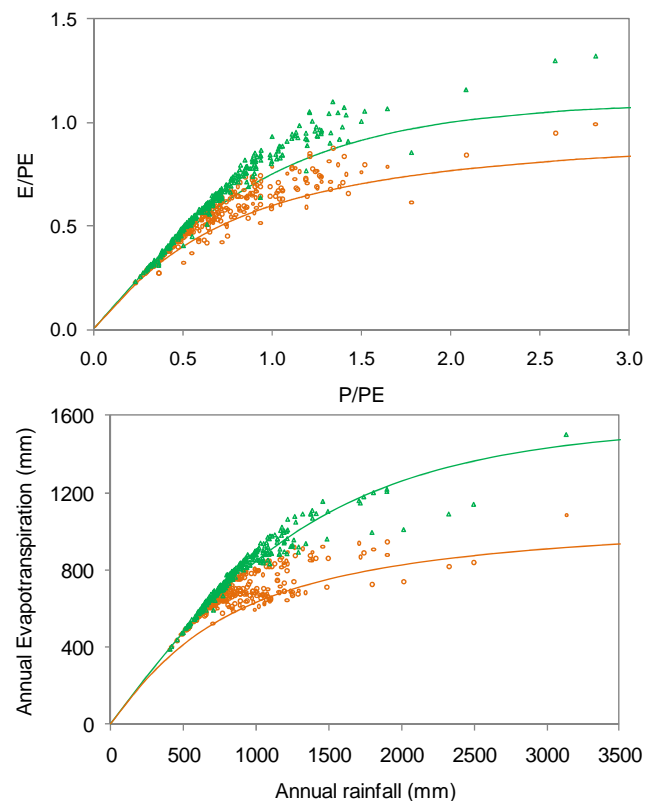


Fig. 2. Comparison of AWRA-L simulated mean streamflow for the 278 catchments for scenarios of forest cover (green triangles) and herbaceous cover (orange circles) shown in two different ways. Also shown are the two models proposed by Zhang et al. (2001): (top panel) Zhang-A and (bottom panel) Zhang-B.

with actual FC values, the resulting values were much closer, at 2.22 and 1.79, respectively, predicting only a very small land cover influence (average forest water use is only 2 % greater than herbaceous water use). This shows that previous contrasting findings can also be reproduced with the synthetic Q data.

3.2 Measurement errors are at least partly responsible

The introduction of noise in the data led to higher average optimised w values than for the experiment without noise added: 2.7 (range 0.6–9.4) for forest and 2.3 (1.3–9.2) for herbaceous cover. Importantly, for 39 % of the 3000 replicates, the optimised w value for forest was actually lower than for herbaceous cover. It follows that random errors in the observations reduce the likelihood that land cover influence is detected, let alone accurately quantified.

3.3 Underlying climate factors may be responsible

The distribution of w values calculated from simulated Q for individual catchments appeared approximately log-normally distributed and therefore all values were log-transformed

before step-wise regression analysis. The ratio P/PE itself did not explain significant variance in either land cover scenario ($r^2 < 0.04$).

Somewhat unexpectedly, the most powerful predictor of variation in w values varied between the forest and herbaceous cover scenarios. In the full forest cover scenario, PE itself explained 45 % (r^2) of the variance in log-transformed w values (see Fig. 3a). Other predictors did not explain any of the residual variance. In the full herbaceous cover scenario, depth-weighted average event precipitation (DWAEP, calculated as the sum of squared daily rainfall totals divided by total rainfall) explained 33 % of the variation (Fig. 3b). Alternatively, mean event precipitation (total rainfall divided by the number of rain days) explained 27 % of variation (instead of, not in addition to the variation explained by DWAEP). Both are indicators of the irregularity of rainfall distribution (see van Dijk, 2010c for definitions). Other predictors did not explain any of the residual variance.

It is concluded that other climate factors than only the ratio P/PE may have considerable influence on Q and hence affect fitted w values. We speculate that the explicit consideration of temporal climate patterns may also be the main reason why the (uncalibrated) process model was slightly more skillful at reproducing observed Q from the 278 catchments than the (calibrated) Zhang model.

3.4 There is structure in the data set that is at least partly responsible

Using simulated Q for randomly generated hypothetical forest cover fractions ($N = 3000$), Zhang model parameter values of 3.4 ± 0.7 (range 1.9–6.1) and 1.1 ± 0.1 (0.9–1.4) were fitted for forest and herbaceous cover, respectively. These average values are relatively close to the w values of 3.6 and 1.0 fitted for the full forest and herbaceous cover scenarios (experiment 1). In some experiments the optimised Zhang parameters were similar to the full cover ones, whereas in other experiments they were very close to each other (Fig. 4a) (it is noted that $w(\text{herbaceous})$ never exceeded $w(\text{forest})$, unlike in the measurement error experiment). It would be tempting to conclude that the covariance between FC and P/PE in the original data set ($r = 0.44$) was the main cause for the underestimation of land cover influence. However, no relationship was found between the fitted parameter pair and the covariance between forest cover and P/PE that was introduced into the data set (Fig. 4a). Nonetheless, our manipulation of the data must have introduced another form of hidden structure in the data that affected the optimised parameter values.

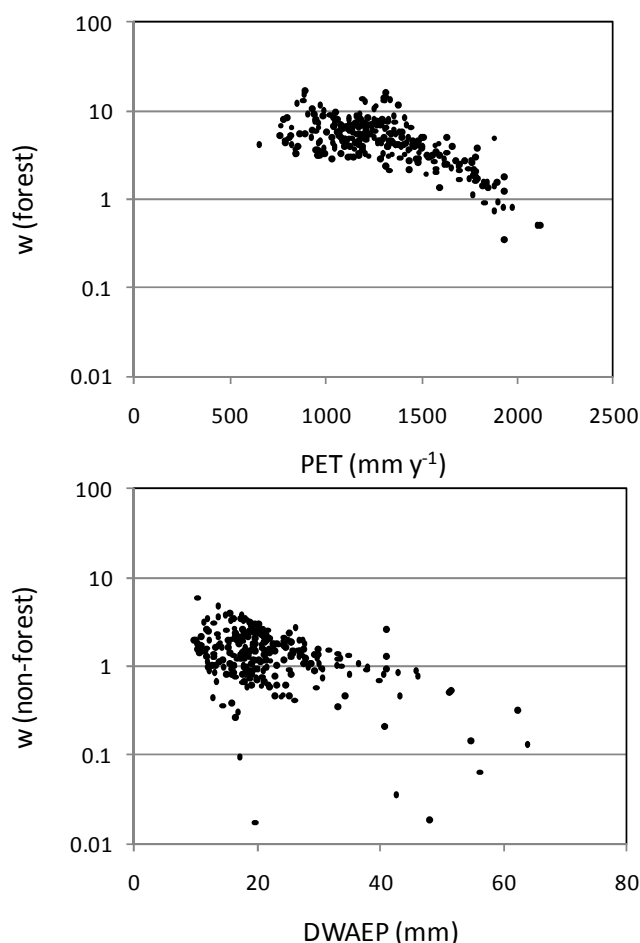


Fig. 3. Relationship between the catchment variable that explained most of the variance in (log-transformed) Zhang model parameter (w) values inferred from the synthetic land cover experiment, (top panel) potential evaporation (PE) for forest catchments and (bottom panel) depth-weighted average event precipitation ($DWAEP$) for herbaceous catchments.

4 Discussion

4.1 Methodological problems can explain previous contrasting findings

Despite their simplicity, Budyko models have shown impressive skill in predicting Q from P and PE alone, when compared to more complex dynamic catchment models. Indeed in comparison with the more complex AWRA-L model, the Zhang model could achieve very similar performance in explaining the observed Q , albeit after parameter fitting. It was this same fitting, however, that produced land cover parameter values that could not be reconciled with the results of experimental catchment studies, thus reproducing previous contrasting findings. We showed that the dynamic hydrological process model could resolve this inconsistency, and therefore, that there appear to be methodological problems with

the use of Budyko models as a detection method in this particular application.

The synthetic experiments demonstrated that all methodological issues tested (measurement errors, the presence of other important uncontrolled factors, structure in the catchment data set) were plausible and can contribute to a failure to accurately quantify land cover influence with the Budyko model that was used. In all cases, underestimation of the land cover influence was the most likely result. Desirable aspects of Budyko models are their conceptual simplicity and the minimal number of parameters. However, in qualifying the principle of Occam's Razor, Albert Einstein (1934) proposed that "the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience". On the basis of our results we conclude that, for the purpose at hand, Budyko models fail at the second part of this statement; that is, they are too simple to adequately quantify the influence of land cover in collated Q data from catchments with mixed land cover.

Although we only tested one particular Budyko model, previous studies suggest that conclusions would likely have been very similar if any other Budyko model had been used, due to the identical conceptual structure and similar function form (see e.g. Oudin et al., 2008). Moreover, we argue that the methodological issues with heterogeneous data sets such as the one we analysed are probably not limited to Budyko models but likely to extend to similarly simple top down inference methods.

There have been attempts to increase the predictive performance of the Budyko models by including additional variables, often within a stochastic framework (e.g. Porporato et al., 2004). Those not related to land cover include absolute PE values (Peel et al., 2010), solar radiation, phase differences between the seasonal P and PE patterns (Donohue et al., 2010), and the daily distribution of precipitation (see review in Gerrits et al., 2009). Our results suggest that some of these factors may indeed exert a similarly large or larger influence on catchment response than land cover. However, trying to control for these additional factors introduces further parameters and observed or estimated attributes with associated uncertainty. Ultimately such an approach must fall prey to the very issue that top-down approaches aim to avoid, that is, an underdetermined (or undetermined) problem in which competing hypotheses create similar outcomes and therefore cannot be tested conclusively.

This is obviously certainly not avoided by the use of dynamic process models. An advantage of such models, however, is that process assumptions can be made more explicit and individually tested against different types of observations with different spatial and temporal characteristics. In light of this, we question whether it is advisable to fit a simplified hydrological model to collated heterogeneous Q data such as the data analysed here. Arguably, it is more pertinent to demonstrate that the observations can be explained satis-

factorily by a (more, but not unnecessarily complex) theory and therefore are not falsified by experimental knowledge. In this context, the Budyko framework may be a valuable benchmark test, whose predictive power should be matched or exceeded by any competing theory (cf. van Dijk and Warren, 2010). It is however perhaps less advisable as inference method to detect second order drivers in heterogeneous data sets.

Strictly speaking, our results are only valid for one particular data set. However, all factors we investigated negatively affected accurate quantification of the land cover influence. We consider it inevitable that at least some of these problems will be encountered in any Q data set from large catchments with mixed land cover. Zhang et al. (2001) showed that this need not prevent detection of land cover impacts in data from catchments that represent extreme scenarios and in controlled experiments. Paired catchment experiments in particular are much more likely to adequately control for climate and terrain factors and thereby allow accurate quantification of the land cover influence. Apart from experimental issues associated with such necessarily small-scale experiments (e.g. subterranean leakage), a critical issue in the extrapolation of the results from such experiments will be the degree to which hydrological processes and land cover characteristics are representative for those in larger, non-experimental catchments (see van Dijk and Keenan, 2007 for a discussion). More elaborate process models may have a role to play here, as the influence of such representational errors can be investigated in model experiments.

4.2 Potential physical causes for reduced land cover influence in catchments with mixed land cover

We did not set out to explore possible physical rather than methodological causes for the inability to adequately detect a land cover influence in previous Budyko model applications in multiple mixed land-cover catchments. They can certainly play a role. The AWRA-L model was not suitable to explore all potential processes in-depth; for example, it cannot simulate land surface-atmosphere feedbacks, and observations were not available to parameterise the impacts of human interferences (e.g. farm dams, roads and soil management) and lateral water redistribution within hill slopes and in the river system. Streamflow routing per se (that is, the accumulation and propagation of streamflow through the river network) has no influence on long-term average Q , but the spatial redistribution of water in the landscape does create a potential for Q to be reduced, e.g. by greater evaporation from streams and riparian areas and the lateral redistribution and subsequent evapotranspiration of surface and sub-surface water at hill slope level. A simple model experiment was performed to assess the possible magnitude of these processes by (i) changing the AWRA-L model code to reroute all lateral flows (surface, soil and groundwater) from the herbaceous to the forest landscape component; (ii) running the

model across all catchments, varying the catchment fraction of forest from 0–100 %; and (iii) comparing the resultant Q estimates to those obtained in the case without redistribution as a reference. The experiment is similar to that reported on by Vertessy et al. (2002), and can be interpreted as a case in which forest is preferentially located in the catchment valleys, maximising its potential streamflow impact by intercepting and lateral flows from upslope areas with herbaceous vegetation. The reference case (i.e. that used in all previous experiments) can be interpreted as a case where any of the hill slopes within a catchment are either fully with or without forest, in which case the forest impact scales linearly with the area under the forest. The results (Fig. 5) show that, according to the model, a considerable departure from the reference case is plausible, in line with previous modelling results reported by Vertessy et al. (2002, their Fig. 3). Climate humidity was a strong determinant of the relative influence of lateral interactions; the strongest non-linear response was predicted for the driest catchments (top curve in Fig. 5), whereas the wettest catchments showed an approximately linear response (bottom curve). Importantly, the results predict that a small fraction of forest can cause a disproportionate reduction in Q , which can indeed lead to an underestimation of land cover influence from analysing mixed land-cover catchments. It is noted that this model experiment likely overestimates the importance of land cover configuration. Firstly, the scenario tested is extreme and in contrast with actual land cover distribution in the catchments, which tend to have most of the forested area on the less accessible and less productive hill slopes and tops. Secondly, we are not able to validate the magnitude of the model-predicted fluxes against experimental data. Indeed, the potential effectiveness of deep-rooted vegetation in intercepting lateral flows from upslope has been speculated on and predicted with models several times (e.g. Stirzaker et al., 2002) but so far rarely observed in reality (e.g. McJannet et al., 2000; van Dijk et al., 2007).

An examination of the main model-predicted causes of Q change associated with land cover change may provide some further insight into reasons why large catchments with mixed land cover might behave differently from small, homogenous (experimental) ones. The model predicts that the main cause of the different hydrological response is the greater rainfall interception loss from forest vegetation (Fig. 6). The difference represents around 10–15 % of rainfall; consistent with the majority of published experiments (e.g. Roberts, 1999; although much greater differences can occur under maritime conditions, e.g. Schellekens et al., 1999; McJannet et al., 2007). A priori it would seem plausible that that the associated rapid return of moisture to the atmosphere may influence rainfall generation downwind (cf. D'Almeida et al., 2007; Pielke et al., 2007; van Dijk and Keenan, 2007). If this is indeed the case, then accurate prediction of the influence of land cover change on the water balance of large catchments may depend on the spatial distribution of precipitation and how it is measured and represented in models. In other

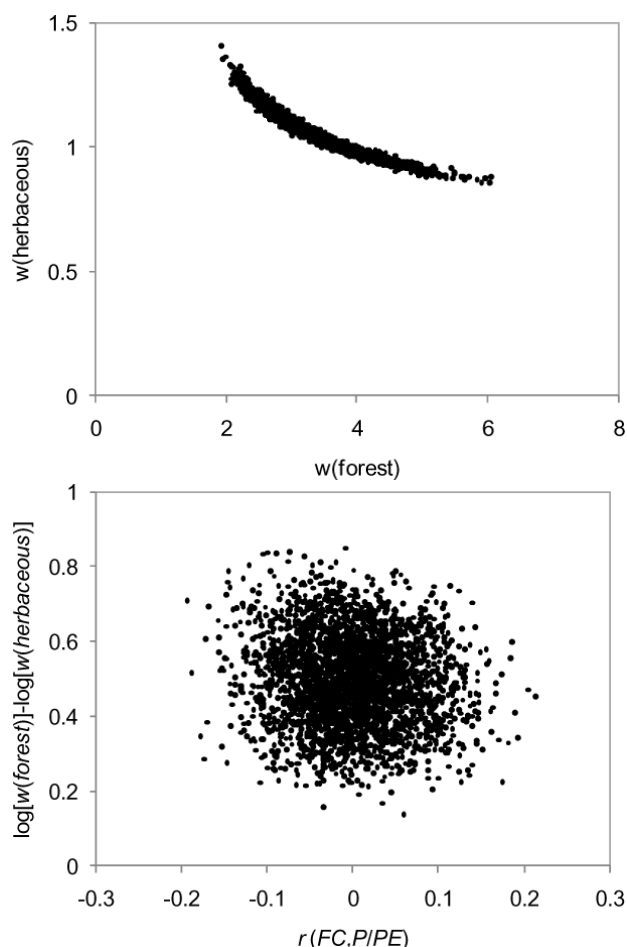


Fig. 4. Zhang model parameter values fitted to synthetic mean streamflow estimates for 278 catchments produced by AWRA-L with random forest cover fractions assigned to each of the catchments. Data points represent the results of 3000 replicate experiments. (Top panel) Zhang model parameter data pairs fitted in each experiment showing a well-defined relationship; (bottom panel) the difference between log-transformed parameter values versus the correlation between synthetic forest cover fraction (FC) and catchment humidity (P/PE) introduced in the experiment, showing no relationship ($r = 0.11$).

words, in sufficiently large catchments the rainfall interception effect might be mitigated by rainfall recirculation.

Finally, it is emphasised that the interpretation of our model results, and particularly those presented in this section, are contingent on the algorithms, assumptions and parameterisations of the process model we used here. We believe it very likely that the methodological problems with the inference method investigated here would be confirmed if other realistic process model structures or parameter sets were used. However, the predicted magnitude of the influence of lateral interactions and the relative importance of rainfall interception loss are likely to be more sensitive to model structure and assumptions, and therefore more speculative.

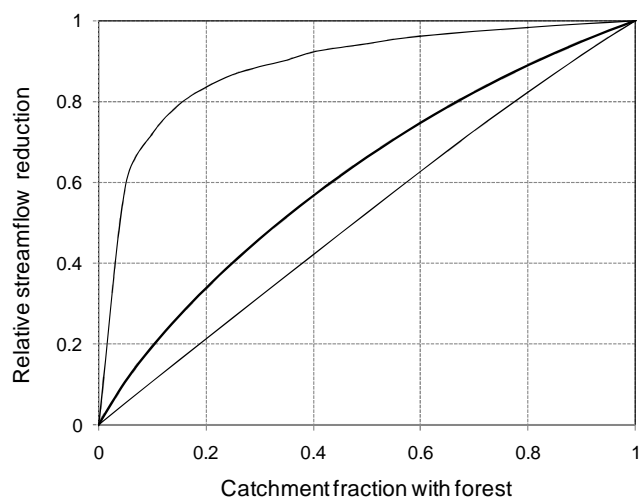


Fig. 5. The theoretical maximum influence of lateral water redistribution, from herbaceous to forest areas, on mean streamflow (Q) as predicted by the AWRA-L model for 278 Australian catchments. The middle bold and two outer lines represent the catchments with the median and most extreme responses, respectively. Q reduction is shown relative to the difference between the 0 and 100 % forest cover cases (in the absence of redistribution a linearly proportional influence would be predicted).

5 Conclusions

Controlled experiments provide strong evidence that changing land cover (e.g. deforestation or afforestation) can affect mean catchment streamflow (Q). By contrast, a similarly strong influence has not been found in studies that interpret Q from multiple catchments with mixed land cover. One possible reason is that there are methodological issues with the way in which the Budyko framework was used in the latter type studies. We examined this using Q data observed in 278 Australian catchments and by making inferences from synthetic Q data simulated by a hydrological process model (the Australian Water Resources Assessment system Landscape model). We draw the following conclusions:

1. Carrying out synthetic experiments with the process model, we could reproduce the absence of a detectable influence in mixed land-cover catchments as well as the presence of such an influence in individual catchments. In other words, previous contrasting findings could be reconciled.
2. Several potential methodological problems with the Budyko framework based inference approach applied in previous studies were investigated. The apparent absence of a detectable influence when comparing mixed land-cover catchments could, at least partially, be explained by the three factors investigated, viz. (i) noise in land cover, precipitation and Q data; (ii) additional catchments climate characteristics more important than

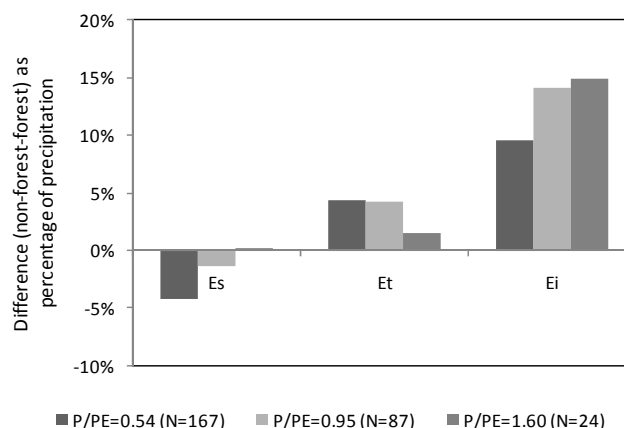


Fig. 6. Contribution of different evaporation terms to the increase of mean streamflow after forest removal estimated by the AWRA-L model, expressed as a percentage of rainfall. Values represent fluxes averaged over three groups of catchments, intended to represent (from left to right) water-limited ($P/PE < 0.75$), transitional, and energy-limited ($P/PE > 1.25$) environments. Es = soil and open water evaporation; Et = transpiration; Ei = rainfall interception losses.

land cover; and (iii) covariance between Q and catchment attributes. Such methodological issues are likely to be found in any heterogeneous streamflow data set.

3. In addition to these methodological issues, there are also plausible physical causes for the failure to adequately detect a land cover influence in catchments with mixed land cover. This includes the lateral redistribution of water from herbaceous to forest areas, and potential recirculation of rainfall intercepted by the forest canopy.

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